ABSTRACT

of the Thesis «Global Practical Tracking for High-Order Uncertain Nonlinear Systems and Creating Program Complex for them» represented by Tasbolatuly Nurbolat in candidacy for a degree of doctor (PhD) in specialty «6D070400 – Computing Engineering and Software»

Relevance of the research topic. Currently, one of the pressing problems of control theory is the automatic control of tracking systems. Tracking systems are widely used in automatic control of autopilots, control of missiles or unmanned aerial vehicles (UAVs) along a predetermined path, automatic temperature control in the chemical industry, automatic adjustment of the position of absorbing rods in nuclear reactors, control of robotic manipulators in production, etc. with this, it plays an important role in control theory. Currently, it is relevant to study the effective use of UAVs, such as quadrocopters or hexacopter, in agriculture or in the delivery of medical supplies to people in the disaster area. Full knowledge of control systems allows you to simulate many complex systems.

Nonlinear systems are an important branch of control theory. All physical systems found in nature are nonlinear. Linear systems are used to describe and control the system, provided that the system does not deviate from the nominal set of current states. Otherwise, the linear model is not considered effective and we will not get the desired results. In this case, nonlinear systems are used. This is because nonlinear controls can directly control large nonlinear systems. Even if the rank of the system is small enough, linearization is not always possible, because there are systems whose linear state is not controlled at any equilibrium point. For such systems, control theory should be used. There are many types of mathematical analysis tools in the theory of nonlinear control. Due to the lack of a universal mathematical method or tool for non-linear analysis, the research topic is relevant.

In the dissertation, *p*-normal nonlinear systems belonging to the same class of nonlinear systems were studied, their stability, asymptotic stability, stabilization of system states, control and tracking problems were studied. As a result of the study, the computer simulated the problems of stabilization of the states of *p*-normal nonlinear systems with dynamic feedback on the output, the problem of controlling the output of a *p*-normal nonlinear system, as well as the task of controlling a *p*-normal nonlinear system with a time delay.

The study of the stability of linear or nonlinear systems and their control, as well as the theoretical results of mathematical modeling of control, are based on the classical works of prominent Soviet scientists, such as A.M. Lyapunov, L.S. Pontryagin, Y.N. Roytenberg, E.A. Barbashin, N.N. Krasovsky, N.G. Chetaev, I.G. Malkin et al. Prominent Kazakhstan scientist doctor of technical sciences, professor T.N. Biyarov once conducted a lot of research in this area and founded the school of control theory. Currently, there are a number of domestic scientists involved in control problems: M.T. Dzhenaliev, S.A. Aisagaliev, Z.N. Murzabekov, Sh.A. Aypanov, M.N. Kalimoldaev, T.Zh. Mazakov et al. The works of scientists from near and far abroad are also of interest in whose works the problem of stabilization

of systems with the help of feedback was first studied: C.I. Byrness and A. Isidori (1989, 1991), J. Tsinias (1989), R. Marino and P. Tomei (1995), M. Krstic (1995) and others. Scientists who are studying the tracking problem using dynamic feedback Q Gong, C. Qian (2005), K. Alimhan, H. Inaba (2003, 2006, 2008), N. Otsuka (2011, 2012-2019), etc.

The problem of control nonlinear systems has been of great interest to the scientific community in recent decades. Over the past two decades, there have been significant positive changes in the development of various methods of the theory of nonlinear control and their results in computer modeling. Firstly, this success is due to the rapid development of computer technology and increased requirements for quality control, which allows you to fully and quickly study nonlinear processes. Secondly, the theory of synthesis and analysis of systems develops from year to year. The relevance of the topic of global practical tracking by uncertain nonlinear systems and the task of creating a software complex for them is directly related to the fact that we mainly use foreign software and hardware to solve applied problems of control and tracking of technical systems in Kazakhstan. For our country, which has chosen the path of industrial and innovative development, the relevance and practical value of studying control / tracking problems to ensure the stability and safety of technical equipment in industries plays a large role.

The purpose of the thesis. To develop an algorithm for finding control of *p*-normal nonlinear systems of high order, using the found control to track the output signal of nonlinear systems behind the estimated reference signal and create a software complex for tracking tasks.

Research Objectives:

- solve the problem of global asymptotic stabilization of indefinite nonlinear systems using output feedback;
- development of an algorithm for finding control tracking a given reference signal of nonlinear systems and nonlinear systems with a time delay;
- according to the developed algorithm, find a control that will track the output signal of the nonlinear system for a given reference signal;
- depending on the control parameters, analyze the tracking and stabilization errors of nonlinear systems and nonlinear systems with a time delay, create a software complex for numerical experiments performed in accordance with control algorithms.

Object of study. Uncertain nonlinear systems of high order and indefinite nonlinear systems of high order with time delay.

Subject of study. Control algorithms for *p*-normal nonlinear systems and *p*-normal nonlinear systems with a time delay parameter.

Research Methods. Feedback method, Lyapunov systems control methods, recursive method, numerical method, uniform domination method, induction method, double compensator-regulator method, Lyapunov-Krasovsky method, Euler method, Runge-Kutta method.

The scientific novelty of the study.

- in the dissertation, a control detection algorithm was developed that monitors a given reference signal of *p*-normal nonlinear real systems, where p> 1;

- using the developed algorithm, a computer model has been created for stabilization, tracking a high-order nonlinear system;

- an algorithm was developed and a computer model for finding control of real nonlinear systems that tracks a given reference signal;

- created a software package for stabilization, control and tracking of nonlinear systems.

Theoretical and practical significance of the results. The results obtained in the dissertation research can be used in the control of electromechanical systems found in the field of industrial technology, science and education, and the developed software can be used in distance learning systems. Many technical devices can be described by mathematical models and algorithms for their solution, developed as a result of dissertation research. For example, electronic systems and equipment, electromechanical systems, unmanned aerial vehicles, space technology, robotic systems, etc.

The main provisions to be defended. An algorithm is proposed for solving the problem of global asymptotic stabilization of the output signals of nonlinear systems of simple form, and an experiment is conducted to stabilize the movement of a single-link robot manipulator, the mathematical model of which is specified by a simple nonlinear system. In addition, a mathematical model was developed to find the control equation for tracking the output signal of high-order indefinite nonlinear systems in *p*-normal form, and a computer simulation algorithm, a block diagram, and numerical experiments were performed. Examples of tasks developed in separate applications were grouped into a software complex and hardware and software capabilities were studied.

Personal contribution of the researcher. The problem of stabilization, control, and tracking of real nonlinear systems, which does not fit into the linearization under study, requires considerable work. Basically, the work was carried out jointly with a scientific consultant and a foreign scientific consultant. In the dissertation, the applicant made a significant contribution to the development of control algorithms that provide tracking of the output signals of nonlinear systems for the reference signal and in the creation of a software package.

Volume and structure of the dissertation. The dissertation consists of an introduction, three chapters, conclusion, list of references and three appendices. The total research volume is 98 pages, including 36 figures, 5 tables.

The first section analyzes the work of scientists on the topic of research and explores the problems of stability of nonlinear systems, control of nonlinear systems using state feedback or output feedback, which are the basis of the dissertation.

In the second section, the concepts of homogeneous systems necessary for research are given and the basic mathematical lemmas are presented. Next, the problem of a wide range of practical control of high-order nonlinear systems was investigated. In particular, a mathematical model is determined for controlling the output signal of non-linear systems of *p*-normal form using the direct Lyapunov method. Computer modeling was carried out using the MatLab program. An example of a solution to control the output signal when all or some of the states of the system cannot be measured is considered. In addition, the problem of tracking a

given reference signal using a state signal in which the state of the system can be measured was considered. A mathematical model of the problem of controlling the state signal using feedback has been developed, and the algorithm has been proved using a numerical experiment. The problem of controlling nonlinear systems of *p*-normal type with a time delay is also studied. Control and monitoring of a nonlinear system with a time delay was carried out using the Lyapunov-Krasovsky method to eliminate the negative consequences of delays in the system. Computer numerical experiments were performed in the MatLab application. A mathematical model of the hardware structure of the equation of motion of a single-link industrial robot manipulator is obtained, coordinate substitutions are introduced, and an algorithm for finding stabilization control of the resulting states of the system is found. Numerical calculations were carried out in the MatLab application using the motion control of a single-link robotic arm.

The third section describes the work on creating a software package for the tasks considered in the dissertation.

In conclusion, the main conclusions and results of the work are formulated.

Testing the results of the dissertation. The main results of the study were presented and discussed at the following conferences and seminars:

- XVI International scientific-practical conference "Problems and prospects of modern science" (2017, Moscow, Russia);
- Scientific conference "Modern Problems of Informatics and Computer Technology" of the Institute of Information and Computing Technologies (June 29-30, 2017, Almaty, Kazakhstan);
- II International Scientific and Practical Conference "Informatics and Applied Mathematics" (September 27-30, 2017, Almaty, Kazakhstan);
- SIBERCON 2017 and XIII International Asian School-Seminar "Problems of Optimizing Complex Systems" (September 18-22, 2017, Novosibirsk, Russia);
- III International Scientific and Practical Conference "Informatics and Applied Mathematics" (September 26-29, 2018, Almaty, Kazakhstan);
- IV International Scientific and Practical Conference "Informatics and Applied Mathematics" (September 25-29, 2019, Almaty, Kazakhstan);
- MATEC web conferences (May 25-27, 2018, Beijing, China);
- Scientific and practical seminars on the topic "Actual problems of computer science, mathematics and management" of the Institute of Information and Computational Technologies (2017-2020, Almaty, Kazakhstan);
- Scientific workshops of Tokyo Denki University (July-August 2018, Tokyo, Japan);
- Scientific seminars of the faculty "Information Technology" Kazakh National University. Al-Farabi (2017-2020, Almaty, Kazakhstan).

On the topic of the dissertation, 13 articles were published and 1 copyright certificate was obtained:

1. Алимхан К., Калимолдаев М.Н., Тасболатулы Н. Глобальное практическое слежение для неопределенных нелинейных систем // Вестник Казахского национального исследовательского технического университета имени К.И. Сатпаева. – Алматы, 2017. – №2 (120). – С.447-452.

2. Алимхан К., Тасболатұлы Н. Жоғары дәрежелі анықталмаған сызықты емес жүйелерді күшті практикалық бақылау // Вестник Казахского национального исследовательского технического университета имени К.И. Сатпаева. – Алматы, 2018. – №1 (125). – С. 362-368.

3. Алимхан К., Тасболатұлы Н. Уақыт кешігуі бар анықталмаған сызықтық емес жүйелердің шығыс шамасын күй кері байланысы арқылы бақылау // Вестник Казахской академии транспорта и коммуникаций им. М. Тынышпаева. – Алматы, 2019. – №1 (108). – С. 166-174.

4. Alimhan K., Otsuka N., Kalimoldayev M.N., Tasbolat N. Practical output tracking for a class of uncertain nonlinear time-delay systems via state feedback // MATEC Web of Conferences, Volume 189, 10027 (2018), 2nd International Conference on Material Engineering and Advanced Manufacturing Technology (MEAMT 2018). – Beijing, China, 2018. – 8 p.

5. Alimhan K., Otsuka N., Kalimoldayev M.N., Tasbolatuly N. Output Tracking by State Feedback for High-Order Nonlinear Systems with Time-Delay // Journal of Theoretical and Applied Information Technology. – 1 February 2019. – Vol. 97, Issue 3. – P. 942-956. (*CiteScore – 0,67; 33rd percentile)*

6. Alimhan K., Kalimoldayev M.N., Adamov A.A., Mamyrbayev O., Tasbolatuly N., Smolarz A. Further Results on Output Tracking for a Class of Uncertain High-Order Nonlinear Time-Delay Systems // PRZEGLĄD ELEKTROTECHNICZNY, ISSN 0033-2097, V. 95 NR 5/2019. – P. 88-91. *(CiteScore – 0,38; 19th percentile)*

7. Алимхан К., Калимолдаев М.Н., Тасболатулы Н. Робастное практическое отслеживание выхода неопределенных нелинейных систем с помощью компенсатора выхода // XVI межд. научно-практическая конф. «Проблемы и перспективы современной науки». – Москва, 2017. – №16. – С.161-165.

8. Алимхан К., Калимолдаев М.Н., Мамырбаев О.Ж., Тасболатұлы Н. Қатаң емес шарт жағдайында анықталмаған сызықты емес жүйелерді шығыс кері байланысы арқылы кең ауқымды практикалық бақылау // II Международная научная конференция "Информатика и прикладная математика". – Алматы, 2017. – С. 114-129.

9. Алимхан К., Калимолдаев М.Н., Тасболатулы Н. Робастное практическое управление выходных данных неопределенных нелинейных систем с помощью динамической обратной связи // Межд. мультиконференция IEEE SIBIRCON 2017. – Новосибирск, Россия, 2017. – С.18-25.

10. Алимхан К., Калимолдаев М.Н., Тасболатұлы Н. Жоғары ретті анықталмаған сызықты емес жүйелерді шығыс компенсаторы жәрдемінде күшті практикалық бақылау // Научная конференция Института информационных и вычислительных технологий МОН РК. – Алматы, 2017. – С. 14-20.

11. Алимхан К., Мамырбаев О.Ж., Тасболатұлы Н., Аманжолова А.А., Боромбаева А.Б. Анықталмаған сызықтық емес жүйелердің шығыс мәліметтерін кері байланыс күйі арқылы бақылау // III Международная

научная конференция "Информатика и прикладная математика". – Алматы, 2018. – С. 95-106.

12. Алимхан К., Тасболатұлы Н. Анықталмаған сызықтық емес жүйелерге кең ауқымды практикалық бақылау және олар үшін бағдарламалық кешен құру // IV Международная научная конференция "Информатика и прикладная математика". – Алматы – 2019. – 1. – С. 108-117.

13. Алимхан К., Тасболатұлы Н., Ерденова А.К., Ахметкалиева А.С. Айнымалы уақыт кешігуі бар шын мәнінде сызықтық емес жүйелердің шығысын күй кері байланыс арқылы ізге түсіру // IV Международная научная конференция "Информатика и прикладная математика". – Алматы – 2019. – 1. – С. 117-131.

14. Copyright certificate *«Program Complex Robust Tracking of Non-linear Systems by Output Compensator»* 03.05.2019. – №3144.